

Analysis of diesel engine in-cylinder air-fuel mixing with homogeneity factor: combined effects of pilot injection strategies and air motion

Article (Published Version)

Dimitriou, Pavlos, Wang, Weiji, Peng, Jun, Cheng, Li, Wellers, Matthias and Gao, Bo (2014) Analysis of diesel engine in-cylinder air-fuel mixing with homogeneity factor: combined effects of pilot injection strategies and air motion. SAE International Journal of Engines, 7 (4). pp. 2045-2060. ISSN 1946-3936

This version is available from Sussex Research Online: <http://sro.sussex.ac.uk/id/eprint/45557/>

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the URL above for details on accessing the published version.

Copyright and reuse:

Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Analysis of Diesel Engine In-Cylinder Air-Fuel Mixing with Homogeneity Factor: Combined Effects of Pilot Injection Strategies and Air Motion

Pavlos Dimitriou
University of Sussex

Weiji Wang
Univ of Sussex

Jun Peng
University of Hertfordshire

Li Cheng
University of Sussex

Matthias Wellers
AVL Powertrain Ltd

Bo Gao
AVL Powertrain UK Ltd

ABSTRACT

With a view to understanding the air-fuel mixing behavior and the effects of the mixture quality on the emissions formation and engine performance, a new quantitative factor of the in-cylinder air-fuel homogeneity named Homogeneity Factor (HF) has been developed. Its characteristics under various injection conditions and air swirl motions within the cylinder have been investigated with CFD simulation. The results have shown that air-fuel homogeneity is essentially affected by the spatial and temporal fuel distribution within the combustion chamber. Higher injection pressure, longer dwell time and increased pilot fuel quantities can contribute to better mixing quality resulting in increased HF and optimum engine performance with low fuel consumption and soot emissions. With regard to the in-cylinder air motion, increasing swirl ratio enhances the air-fuel mixing quality which has been reflected in the variation of the HF. As a result, increased in-cylinder pressure and temperature caused by the optimized air-fuel mixing improved the combustion efficiency.

CITATION: Dimitriou, P., Wang, W., Peng, J., Cheng, L. et al., "Analysis of Diesel Engine In-Cylinder Air-Fuel Mixing with Homogeneity Factor: Combined Effects of Pilot Injection Strategies and Air Motion," *SAE Int. J. Engines* 7(4):2014, doi:10.4271/2014-01-9052.

INTRODUCTION

Future diesel engines have to be cleaner, less expensive, provide higher power density and be more efficient to be competitive in the marketplace and be environmentally friendly. The combustion control is a key characteristic for economic, clean and powerful DI diesel engines. The combustion process can be controlled directly by the air-fuel mixing quality within the combustion chamber. The common rail (CR) technology has been fairly investigated and used in diesel engines over the last decades in automotive industry. In the late 1960's, the first CR prototype system was developed in Switzerland. However, the first successful application in a production vehicle

came a few decades later, in 1995, by DENSO Corporation which launched a newly developed CR system mounted on the Hino Rising Ranger truck [1]. CR injection system can provide multiple advanced injections per cycle within the cylinder at high injection pressures with flexible injection timing and volumes. The relatively new fuel injection technology has been primary used for reducing the noise level and exhaust emissions of diesel engine [2, 3, 4, 5]. Shuji et al. proved that CR advanced injection strategies could also lead to relative low combustion temperatures and be further beneficial for emissions reduction [6].

Extensive research has been carried out on the beneficial effects of multiple fuel injections within the cylinder chamber. The initial investigations carried out on the effects of pilot injection in the combustion process can trace back in 1995 with works from Pierpont et al. [7] and Minami et al [8] who demonstrated that by having a pilot injection in the combustion process, the ignition delay could be reduced and this led to a lower heat release rate, with less NO_x emissions and combustion noise. Mendez et al. [9] proved that combustion noise and instantaneous fuel burning rate could be decreased by splitting the heat release process as a result of multiple fuel injections per cycle. They also demonstrated that multiple injection strategies could be used for better control of the spatial fuel distribution and enhancing the air use in the combustion chamber. As a result, this could lead to a reduction in particulate emissions at intermediate engine loads. Montgomery et al. [10] showed that multiple injection strategies could reduce NO_x emissions by lowering the peak in-cylinder temperature when combined with exhaust gas recirculation (EGR) into the cylinder. However, the soot emissions were raised due to some increased temperature rich regions created as a result of the oxygen reduction in the cylinder. Park et al. [11] investigated the effects of multiple injections in a HSDI diesel engine equipped with CR injection system. They found that pilot injection reduces the ignition delay for the main injection and enhances the power output by controlling the intensity of premixed combustion. They also noted the importance of the post-injection in completing the oxidation process and reducing the particulate emissions even when small fuel quantities were injected. According to their results, multiple injection strategies could reduce particulate emissions by more than 40% in some cases.

Diez et al. [12] carried out an investigation in a single cylinder optical diesel engine for the effect of split main injection (30% to 70%) with short dwell angle (11.8o CA) and high EGR rates. The results showed improved indicated mean effective pressure (IMEP) and low NO_x emissions. However, owing to too short time between the two main injections the air-fuel mixing quality becomes poor, leading to high unburned hydrocarbon (uHC) and soot emissions. Tow et al. [13] showed the importance of the dwell angle between injections in order to control soot formation and suggested that there would be an optimal dwell angle at a particular operating condition. Mobasheri et al. [14] studied the effects of dwell between two injections and proved that for his testing operating conditions, the optimum dwell angle between the injection pulses was around 20oCA.

For the reduction of soot and NO_x simultaneously to meet future emissions legislation, CR technology can provide a constantly high injection pressure that improves the fuel atomization from the beginning to the end of the injection. Also, the high velocity of the fuel jet and the fuel droplets cause high turbulence energy and therefore reduces the need of swirl energy to reach a necessary mixture formation [15]. Badami et al. [16] studied the effect of fuel injection pressure. They achieved a reduction of particulate emissions up to 27% by

increasing the injection pressure from 1300 to 1500 bar in a HSDI diesel engine at 4000 rev/min. Their results also proved that particulate emissions can be reduced via enhanced spray penetration caused by the injection pressure increase. Agarwal et al. and Gumus et al [17-18] have also proved with their experiments that increasing the fuel injection pressure is effective for reducing the number concentration of particulates along with mass of particulates at all loads. Gumus et al. showed that increased injection pressure causes a decrease in smoke opacity, UHC, and CO, while it causes an increase in the emissions of CO₂, O₂ and NO_x. DENSO cooperation has recently developed and launched a new CR system with injection pressure up to 3,000 bar [19]. According to their research, the new system can increase fuel efficiency by up to 3 percent while also reducing particulate matter by up to 50 percent and NO_x by up to 8 percent compared to their previous generation system [19]. These changes allowed the fuel to atomize into finer droplets, which improved fuel ignition and combustion efficiency, resulting in increased fuel economy and cleaner exhaust emissions.

All the research work mentioned above clearly shows that the fuel injection strategy is crucial for improving the combustion process of diesel engines. However, for air-fuel mixing quality optimization, the in-cylinder air motion generated due to the design of the intake ports should be also taken into account. For instance, Karuppa and Manimaran [20] showed that by varying the swirl ratio from 1.4 to 4.1, the peak pressure, peak temperature and peak heat release rate increased by 7%, 8.6% and 31% respectively. Simultaneously, they proved that by increasing the swirl ratio from 1.4 to 4.1, peak soot level reduced by 30 % but peak NO_x emissions increased by 54 %.

In this paper, the Homogeneity Factor will be used for exploring the effects of pilot injection, fuel pressure, dwell angle etc. on the air-fuel mixing quality, engine performance and emissions formation. The paper is divided in the following categories; firstly the CFD model is validated compared to real engine test results. Then, simulations for six modes with different injection pressure and dwell time between pilot and main injection are performed for various pilot injections. Finally, simulation will be carried to examine the effect of all different swirl ratios to the air-fuel mixing homogeneity.

NUMERICAL METHOD

Sub-Models

Numerical simulations were conducted by using AVL FIRE CFD code for Diesel combustion. The submodels employed in the code have been chosen based on previous researchers' work and it has been suggested those sub-models are appropriate for high fuel pressure diesel combustion.

The atomization of fuel spray can be divided into two separate stages. The primary atomization takes place close to the nozzle and the secondary one occurs further downstream due to aerodynamic interactions. The WAVE and Taylor Analogy

Break-up (TAB) [21] models do not distinguish between the two processes. However, TAB model has not been used since it is not appropriate for cases with high injection pressures (greater than 40MPa) and predicts too small liquid and vapour penetrations. ETAB (Enhanced Taylor Analogy Break-up) [22], FIPA (Fractionnement Induit Par Accelération) [23] or KH-RT (Kelvin Helmholtz-Rayleigh Taylor) [24], are some of the break-up models can be used for predicting the fuel spray atomization. However, these models treat and simulate the primary and secondary regions separately. This fact could cause a difficulty in estimating the correct values for the additional set of tuning parameters. In the code, the primary and secondary atomization of the fuel spray is predicted using the WAVE model [25], which has been widely used for high-speed fuel injections. The WAVE model assumes that the droplet size and the breaking up time is related to the fastest-growing Kelvin-Helmholtz instability [26]. The details of the newly-formed droplets are predicted using the wavelength and growth rate of this instability. The parameters of the model have been tuned to match the experimental data.

For the heat-up and evaporation prediction of the droplets, Dukowicz evaporation model [27] is selected for the simulations with diesel fuel. Dukowicz model determines the rate of droplet temperature change by the heat balance, which states that the temperature transferred from the gas to the droplet supplies heat for its vaporization. The model tunable constants have been adjusted to match the experimental data.

The $k-\zeta-f$ model recently developed by Hanjalic, Popovac and Hadziabdic (2004) [28] was used for the evaluation of the turbulence effect in the combustion chamber. The $k-\zeta-f$ model is widely used in IC flows due to its robustness to be used for computations involving grids with moving boundaries and highly compressed flows. Moreover, for IC flows, the $k-\zeta-f$ model leads to more accurate results compared to the standard much simpler two equation $k-\varepsilon$ [29] and RNG $k-\varepsilon$ [30] models.

ECFM-3Z (Extended Coherent Flame Model - 3 Zones) model [31] was applied for the combustion model of the simulations. ECFM-3Z separates a computational cell in 3 zones in order to enable specific treatment for air fuel mixing, auto ignition, combustion and pollution formation processes. The three different regimes computation aids to a deep understanding of the turbulence flow and provides data inaccessible with experimental devices such as fuel mixture fraction distribution and fuel evaporation rate.

Finally, Zeldovich [32] and the Kennedy, Hiroyasu and Magnussen mechanism [33] were implemented in the software for NO_x and soot formation respectively. The soot formation implemented is based upon a combination of suitable extended and adapted joint chemical/physical rate expressions for the representation of the processes of particle nucleation, surface growth and oxidation.

The list of all the sub-models have been implemented is presented in Table 1.

Table 1. Computational submodels

Break-up model	WAVE model [25]
Evaporation model	Dukowicz [27]
Turbulent model	$k-\zeta-f$ model [28]
Combustion model	ECFM-3Z model [31]
NO _x mechanism	Extended Zeldovich [32]
Soot model	Kennedy, Hiroyasu and Magnussen [33]

Engine Specifications

A light duty diesel engine with compression ratio of 18.3:1 and swept volume of 0.5 litre (per cylinder) is used in this study. A six-hole injector is placed centrally in the test engine to spray the fuel in the combustion chamber. The specifications for the engine and injection system are listed in Table 2 and Table 3.

Table 2. Engine specifications.

Displaced volume	0.5 litre
Stroke	86 mm
Bore	86 mm
Connecting rod	143.5 mm
Compression ratio	18.3:1
Number of valves	4
Inlet Valve Close	64° ABDC
Exhaust Valve Open	69° BBDC
Engine speed	2000rpm
Piston shape	Mexican hat style

Table 3. Fuel injection characteristics.

Injection pressure	800 to 1600 bar
Number of nozzle holes	6
Nozzle hole diameter	0.169 mm
Fuel type	49.1 CN diesel

Computational Grid

The piston and the injector geometry parameters have been set in the software using the 2D Sketcher tool. The computational grid was generated and the model tested under various mesh sizes in order to make sure that the results are grid independent. The grid independence analysis is presented in Figure 1.

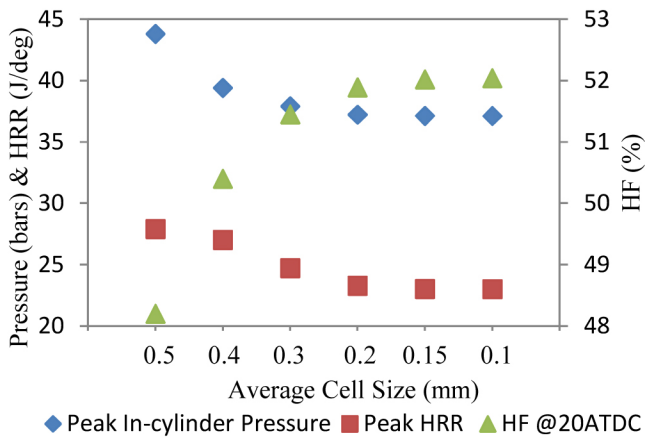


Figure 1. Computational Grid Independence Analysis.

The final grid independent model, shown in Figure 2, has an average cell size of 0.15mm with relatively denser meshing existing closer to the injection tip and the TDC clearance gap. The model consists of 42,052 and 72,052 hexahedral cells at TDC and BDC respectively.

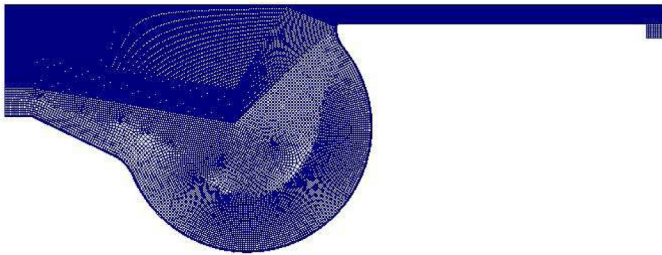


Figure 2. Computational grids at TDC.

Test Conditions

The tests were performed under the following air and fuel conditions. The simulation is carried out on a 60° sector for reduced calculation time due to the symmetric location of the 6-hole injector at the centre of the combustion chamber. Calculation starts at the inlet valve closure (IVC) and ends just before the exhaust valve opening (EVO) for time saving reasons.

Table 4 specifies the air and fuel initial conditions for all the simulations.

Table 4. Initial air & fuel conditions.

Intake air temperature	380 K
Intake air pressure	1 bar
Fuel temperature	350 K
Fuel injected	13.98 mg/cycle
Number of injections	2
Total injection duration	14.6 ° to 20.6° CA
Start of Pilot Injection	19.12° to 5.73° CA BTDC
Start of Main Injection	TDC

Tests were divided into two main categories. The first category involves the study of six different modes with variation of the injection pressure and dwell angle between the injections. The six modes defined below in table 5 were simulated for three different pilot injection quantities of 0.7, 1.4 and 2.8 mg/cycle.

Table 5. Engine test conditions.

Mode	Inj. Pressure (bar)	Dwell Angle (CAD)
1	800	5
2	1200	5
3	1600	5
4	800	15
5	1200	15
6	1600	15

The second set of tests performed analyzes the swirl effect on the air-fuel mixing quality and emissions of the engine. The 6 modes defined earlier were compared for three different swirl ratios of 1.5, 2 and 2.5.

PARAMETER DEFINITION

In this paper, the mixing quality parameter used is one named Homogeneity Factor (HF) which was originally developed by Peng and Liu [34]. The air-fuel mixing quality is measured based on the fuel difference in a calculated cell (e.g. Cell i), compared to the average equivalence ratio:

$$\frac{\Phi_i}{AFR_{st} + \Phi_i} \delta m_i - \frac{\Phi_0}{AFR_{st} + \Phi_0} \delta m_i = \frac{(\Phi_i - \Phi_0) AFR_{st}}{(AFR_{st} + \Phi_i)(AFR_{st} + \Phi_0)} \delta m_i$$

where AFR_{st} is the stoichiometric air-fuel ratio, Φ_i is the equivalence ratio in cell i, Φ_0 is the average equivalence ratio and δm_i is the mass of the mixture in the computational cell i.

The Total fuel amount in the cylinder is,

$$\frac{\Phi_0}{AFR_{st} + \Phi_0} M$$

Then, a parameter named Heterogeneity Factor (HeterF) can be expressed as,

$$HeterF(\theta) = \sum_{i=1}^{N_{cells}} \frac{\sqrt{(\Phi_i - \Phi_0)^2} \delta m_i}{2\Phi_0 M \left(1 + \frac{\Phi_i}{AFR_{st}}\right)}$$

As the increased fuel amount in a cell actually comes from the decrease of fuel amount in other cells, the half of the standard deviation is used in the definition to reflect the non-uniformity more accurately.

Based on HeterF, the homogeneity factor (HF) can be derived for having a quantitative demonstration to the charge mixing quality.

$$HF(\theta) = (1 - HeterF(\theta))\%$$

Compared to Nandha and Abraham's definition for Degree of Heterogeneity (DOH) which actually represents the standard deviation of the equivalence ratio normalized by the overall equivalence ratio [35], the HeterF (heterogeneity factor) is the standard deviation of fuel amount normalized by the overall fuel amount. This will be a more reasonable measure to the non-uniformity in the mixture.

MODEL VALIDATION

The CFD model was validated using experimental data conducted on the single cylinder research engine with the specifications as listed in Table 2.

Figure 3 and Figure 4 show the comparison between the predicted and measured in-cylinder pressure and heat release rate for low load at 1,200rpm and high load at 2,000 rpm respectively. The result is based on the assumption of uniform wall temperature 470 K for the cylinder wall and 570 K for the cylinder head and the piston top.

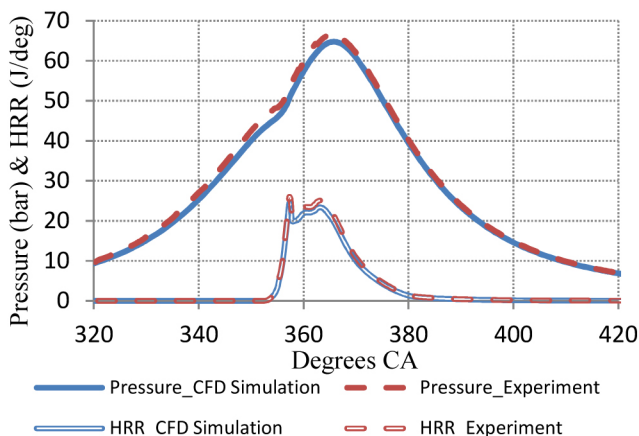


Figure 3. Comparison of simulated and measured in-cylinder pressures and heat release rates for single injection at 1,200rpm, low load.

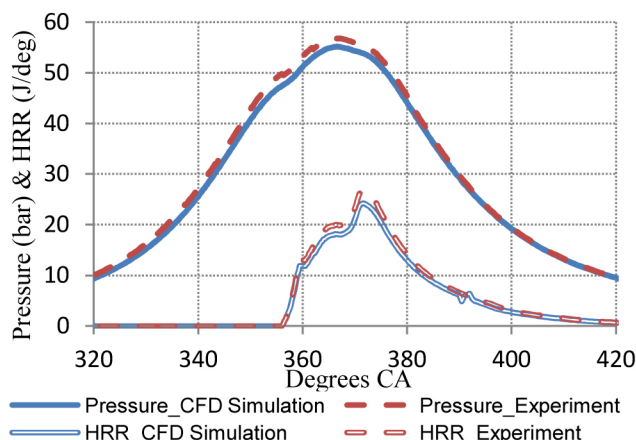


Figure 4. Comparison of simulated and measured in-cylinder pressures and heat release rates for single injection at 2,000rpm, high load.

The CFD simulation trend for the in-cylinder pressure seems to be in reasonable agreement with the experimental measured values for both operating conditions. There is only a slight pressure difference after the start of combustion which might be related to experimental uncertainties in input parameters to the computations such as the precise injection duration, start of injection and gas temperature at the IVC. On the other hand, the calculated heat release rate based on the experimental results seems to follow the same trend as in the simulation. However, the calculated HRR is slightly higher than the simulation experiments and it seems to have a smoother drop after the end of combustion. It is considered that the slight pressure and HRR variations between the experimental and simulation results will have a minimum impact on the results of the in-cylinder mixture homogeneity. A contingent small fuel injection variation will not significantly interfere with the air and fuel flow motions within the cylinder.

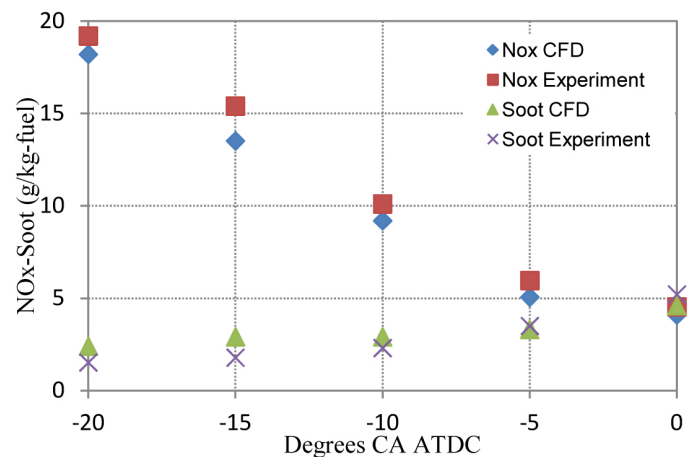


Figure 5. Comparison of simulated and measured NOx and soot emissions for single injection.

Figure 5 presents the comparison of NOx and soot emissions formation for single injection cases with different start of injection timings at 2000rpm. It can be seen that simulation and experimental emission result are nearly matching for the cases where the start of injection occurs close to TDC. For cases with an earlier start of injection, there is a very slight divergence which has possibly been caused by some air motion instabilities.

Figure 6 shows the NOx and soot results gathered for three operating conditions featuring a pilot injection at an injection pressure of 1,600bar and a dwell angle of 5° CA. It can be noticed that the simulation and experimental results for operating conditions featuring pilot injection are not as identical as the results of the single injection cases. This could possibly happen due to variations of the injected fuel mass compared to the simulation model. Injection mass variations can be caused by fuel dribbling after the pilot injection or by failure of the injector's needle to reach its maximum lift due to the very small fuel amount injected during the first pulse. This can be also confirmed by the higher error in the soot and NOx emissions for the cases with very low pilot fuel amount.

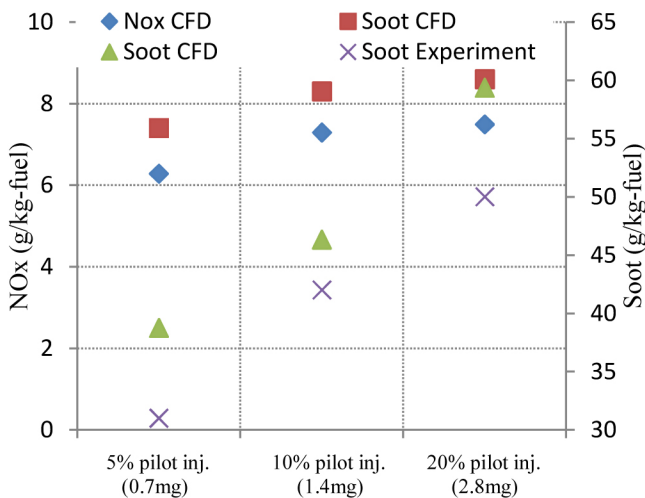


Figure 6. Comparison of simulated and measured NOx and soot emissions for multiple injections.

It can be concluded that simulation results are nearly matching with experimental for single injection cases. At the same time, simulation results for multiple injections follow a quite close trend and are correspondent with the measured values. Thus, the model used in this study can provide enough confidence to the following simulation results with regard to the combustion process and emissions.

RESULTS AND DISCUSSION

Combustion Analysis

The 6 modes were tested for variable injection pressures and dwell angles between the pilot and main injection at three different pilot injection strategies (0.7, 1.4 and 2.8mg/cycle). Figure 7 represents the in-cylinder pressure for all the modes at each injection strategy. It can be clearly seen by looking at the pressure graphs of all six modes that the highest pilot injection quantity produces the highest in-cylinder peak pressure. The in-cylinder pressure also seems to rise slightly as the injection pressure is increased as shown by comparing pressure graphs of Modes 1, 2, 3 and 4, 5 and 6. This is happening due to two main reasons. Firstly, the better fuel atomization corresponding to the smaller fuel droplets size and also the higher momentum of the jet caused by the injection pressure increase which has improved the air-fuel mixing quality [36–37]. The in-cylinder pressure increase caused by those two main factors is leading to a more complete combustion and a more intense heat release rate as shown by comparing the HRR graphs of Modes 1, 2, 3 and 4, 5, 6 in Figure 7. It is also demonstrated that the higher injection pressure and longer dwell angle result in higher average in-cylinder combustion temperatures due to the enhanced air-fuel mixing. Improved mixing has been achieved due to the longer available time between pilot and main injection which resulted to a more complete combustion. From Figure 7, it can also be noticed by comparing the pressure graphs 1, 2, 3 with

4, 5 and 6 that the peak in-cylinder pressure is depended upon the pilot fuel injection timing and is highly affected by the pilot injection fuel quantity.

Figure 7 also shows the rate of the heat release as a function of crank angle degrees at three different injection quantities. It can be clearly seen from the HRR graphs that in Modes 1, 2 and 3 where the dwell angle between the two injections is 5° CA, combustion has not taken place until the point where main injection starts. On the other hand, as shown in the HRR graphs for Modes 4, 5 and 6, the cases with increased fuel quantity benefit from adequate combustion conditions before the injection of the remaining fuel and therefore extend the combustion duration by advancing the premixed combustion phase and extending the mixing-controlled combustion phase. This has a negative impact on the NOx and soot formation as analyzed below.

Homogeneity Factor

It is obvious that the in-cylinder air-fuel mixing quality is the main factor contributing to the performance and emissions characteristics of diesel engine. It is crucial to understand how air-fuel mixture quality can be improved by altering various injection specifications and how this improvement will affect in a positive or negative way the performance and emissions characteristics. The HF parameter used in this work can demonstrate the in-cylinder air-fuel mixing quality of each test at any crank-angle position. Figure 7 compares the air-fuel homogeneity percentage of all six modes for three different pilot injections (0.7, 1.4 and 2.8mg).

It suggests that the more the pilot injection quantity is, within the above ranges, the higher the air-fuel mixing quality. Improved air-fuel mixing in cases with higher pilot injections occurs for two reasons. Firstly, more fuel is injected during the pilot pulse which means that injection needs to start at an earlier point as the dwell angle is kept constant at 5° or 15° CA. Secondly, higher amount of fuel injected during the first pulse leads to a more balanced injection strategy with less fuel injected over the second pulse which reduces the injection time and enables a better fuel particles spread within the combustion chamber. It can be noted from the HF graphs in Figure 7 that the HF rises faster in cases with higher pilot injection quantities as the injection starts at an earlier stage. From the HF graphs in Figure 7, it can also be seen that there is a significant reduction in homogeneity at the point where second injection takes place for Modes 4, 5 and 6. This is happening due to the long dwell angle of 15° CA between the two injections leading to an optimum air-fuel mixture quality before the second injection and a sharp fall during the second pulse. On the other hand, for Modes 1, 2 and 3 with 5° CA dwell, HF keeps raising at a lower ratio than prior the second pulse due to the very short gap between the end of the first and start of the second injection.

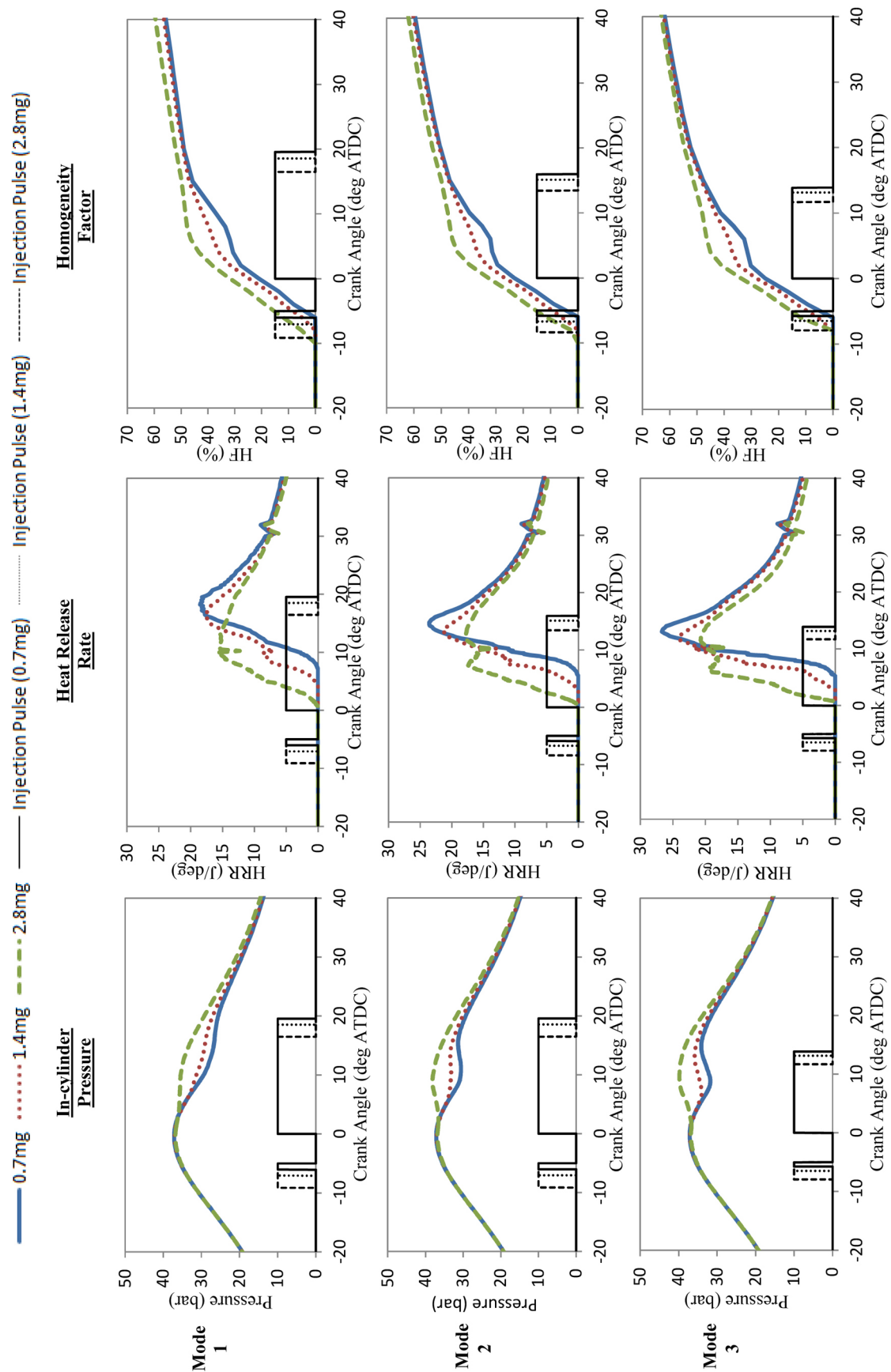


Figure 7. In-cylinder pressure, HRR and HF profiles for different injection modes (see Table 5).

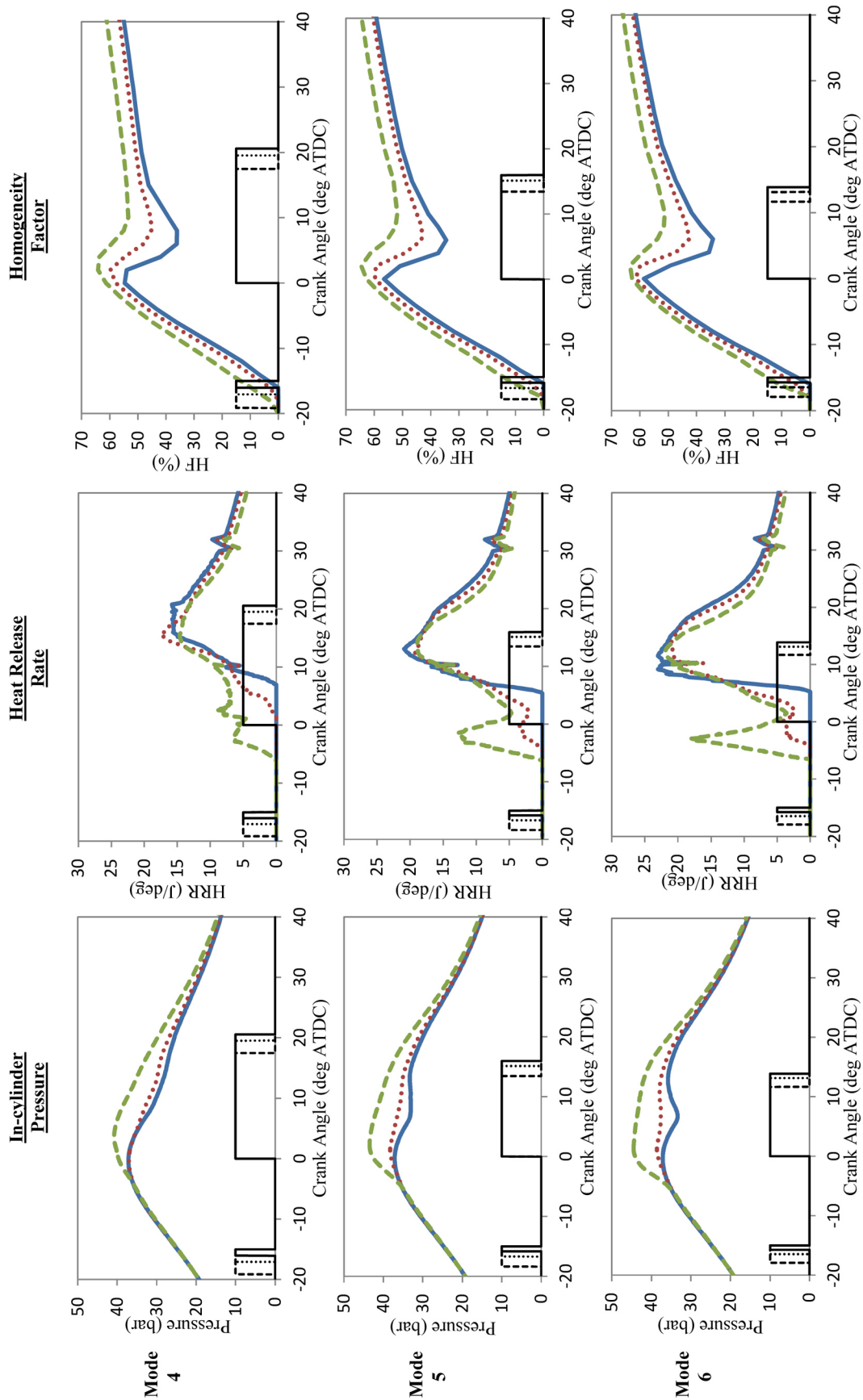


Figure 7. (cont.) In-cylinder pressure, HRR and HF profiles for different injection modes (see Table 5).

Figure 8 illustrates contours of the equivalence ratio for three different Modes (1, 2 and 3) at the point where maximum heat release takes place (375° CA). It can be clearly noticed the effect of injection pressure to the mixing quality. The equivalence ratio shown in the contour for Mode 1 is still at a very high level close to the injector nozzle. As the injection pressure increases, the fuel seems to be spread faster and finer within the cylinder as shown in Modes 2 and 3. The high injection pressure leads to a better fuel atomization and a higher momentum of the jet which as a result lead to a better mixture quality. The better mixing quality for the cases with higher injection pressure can be confirmed by the HF levels. The HF for case with 1,600 bar injection pressure (47.77%) is almost 5% higher than the combustion case with 800bar injection pressure (45.68%).

Figure 9 shows the difference in the mixing quality caused by altering the pilot injection quantity. It seems that high pilot fuel quantities can lead to enhanced fuel stratification. This is due to

the fact that higher amount of fuel has been injected during the first pulse which can be translated to the higher equivalence ratio at the bottom and the sides of the cylinder. The HF rises at 61.58% for the 1.4mg pilot injection case at the TDC compared to 58.59% for the case with 0.7mg pilot quantity. It's clear that the more fuel injected has been spread faster at the bottom and the sides of the cylinder where the equivalence ratios seem to be higher than 0.7mg case. Also, at 15° CA ATDC the HF is 49.81% for the case with 1.4mg of pilot fuel injection compared to 47.49% for the case with 0.7mg of pilot fuel. Comparing the 15° dwell angle contours of Figure 9, it can be noticed that the higher pilot injection quantity has improved the fuel stratification at the bottom and sides of the cylinder. Pilot injection can be used for improving the air-fuel mixture quality and it can be concluded that, within the ranges investigated above, high amounts of fuel injected during the first pulse lead to enhanced air-fuel homogeneity. However, the limit on the maximum amount of pilot fuel can be used for improving fuel stratification needs to be found by sweeping the pilot fuel fraction.

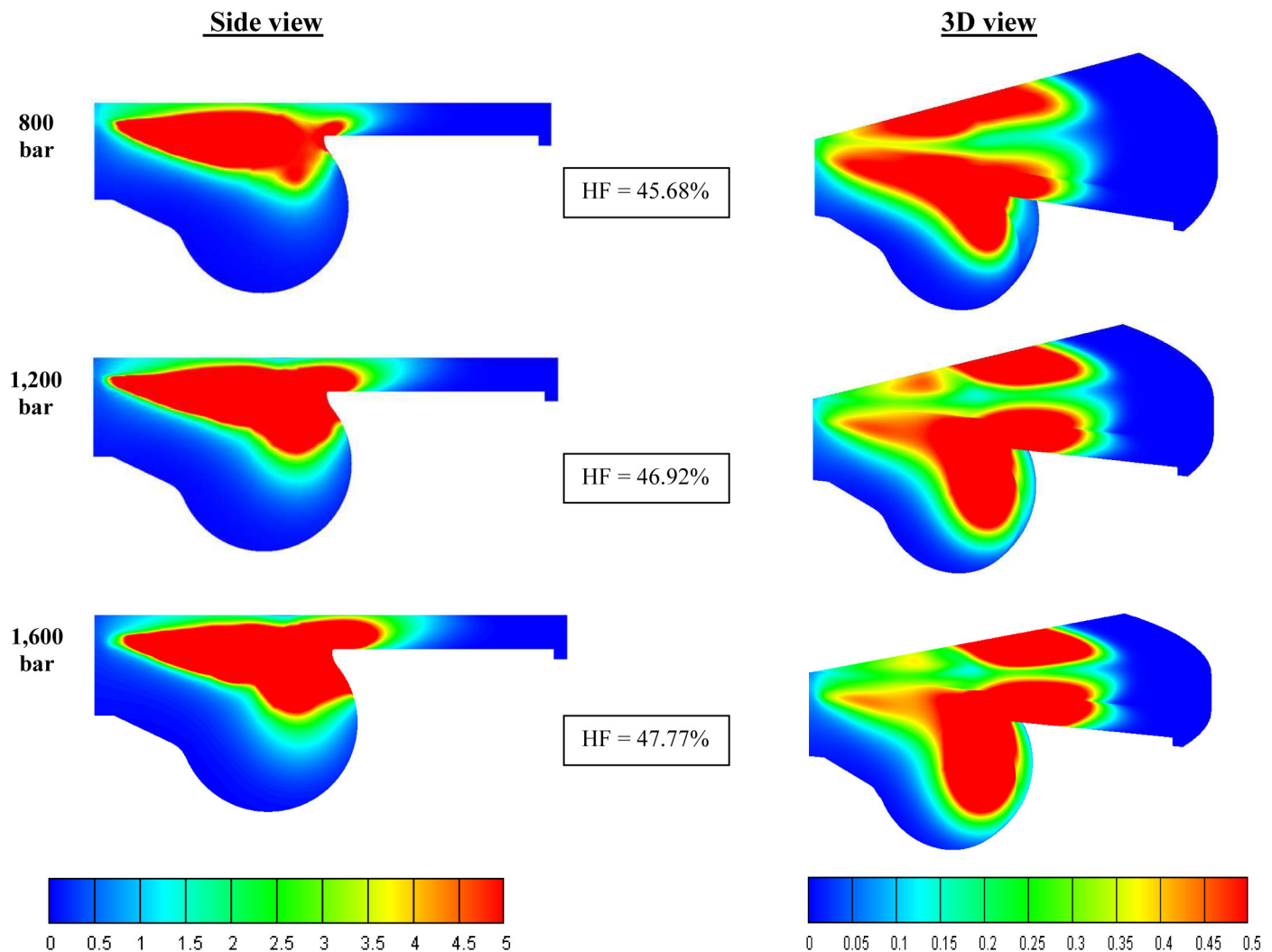


Figure 8. Equivalence ratio contours [side (0-5 range) and 3D (0-0.5 range) views] at 15° CA ATDC for different injection pressures with 5° CA dwell period and 0.7mg of pilot fuel.

Figure 10 represents the contour plots of Modes 3 and 6 with 2.8mg of fuel injected during the first pulse. They show the effect of dwell to the equivalence ratio at the TDC. It can be noted that the fuel spread over the cylinder for Mode 6 is more advanced due to the fact that injection occurred much earlier compared to Mode 3. The fuel has been spread efficiently over the chamber

and the combustion has started in comparison with Mode 3 where pilot injection process has almost been completed and combustion process is still expected. This can be confirmed by the very high number of HF for the case with the longer dwell angle (63.48%) relative to short dwell angle case (33.73%).

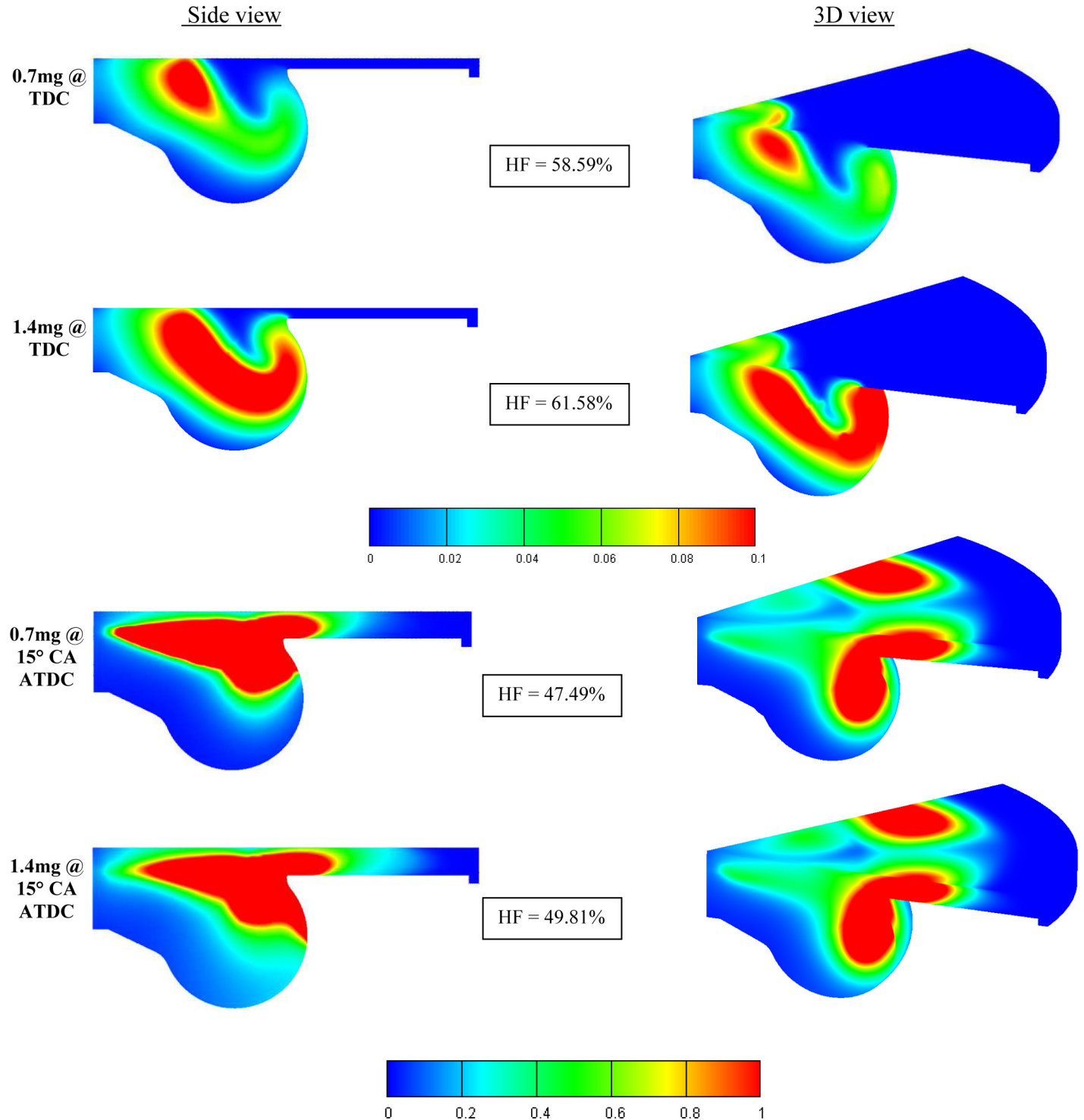


Figure 9. Equivalence ratio contours (side and 3D views) at TDC and 15° CAATDC for different pilot quantities with 1,600bar fuel pressure and 15° CA dwell period.

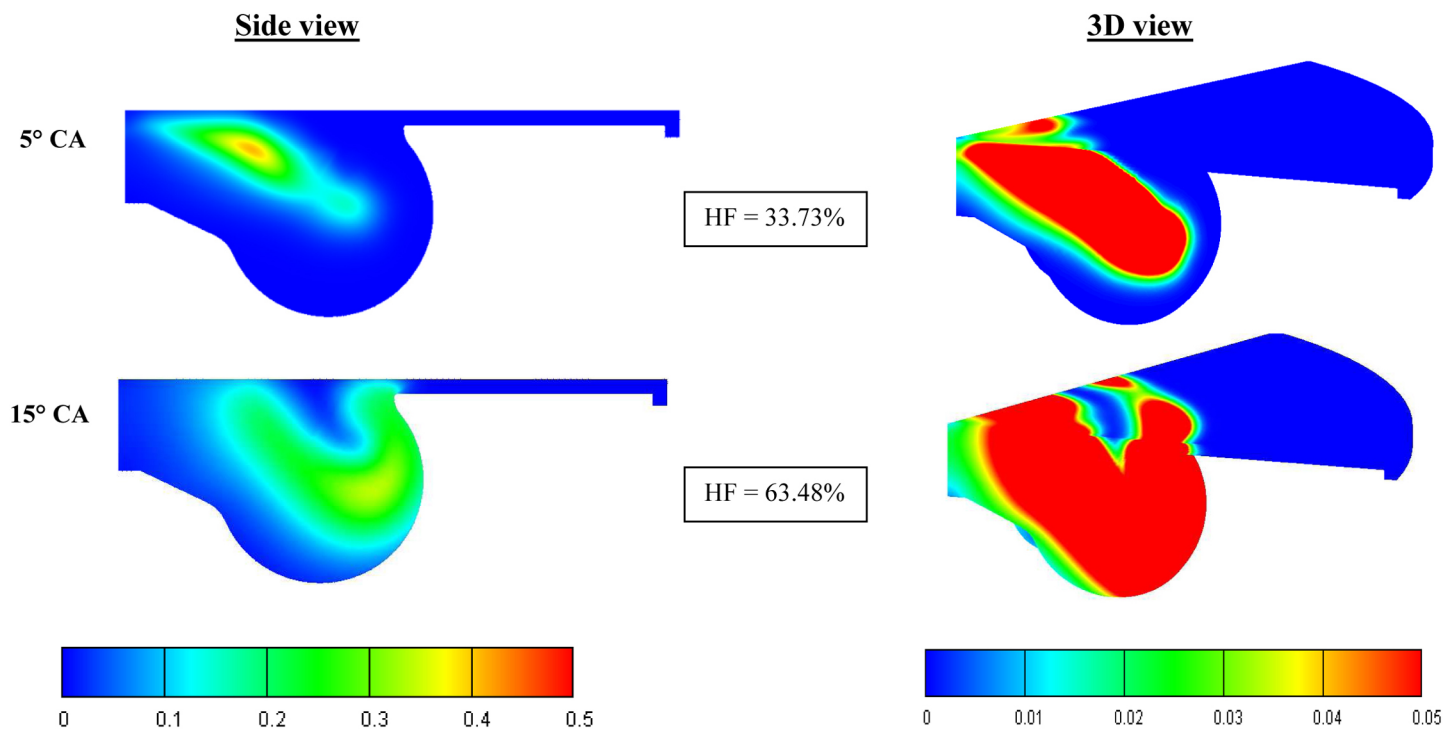


Figure 10. Equivalence ratio contours [side (0-0.5 range) and 3D (0-0.05 range) views] at the TDC for different dwell angles with 2.8mg pilot fuel injection and 1,600bar injection pressure.

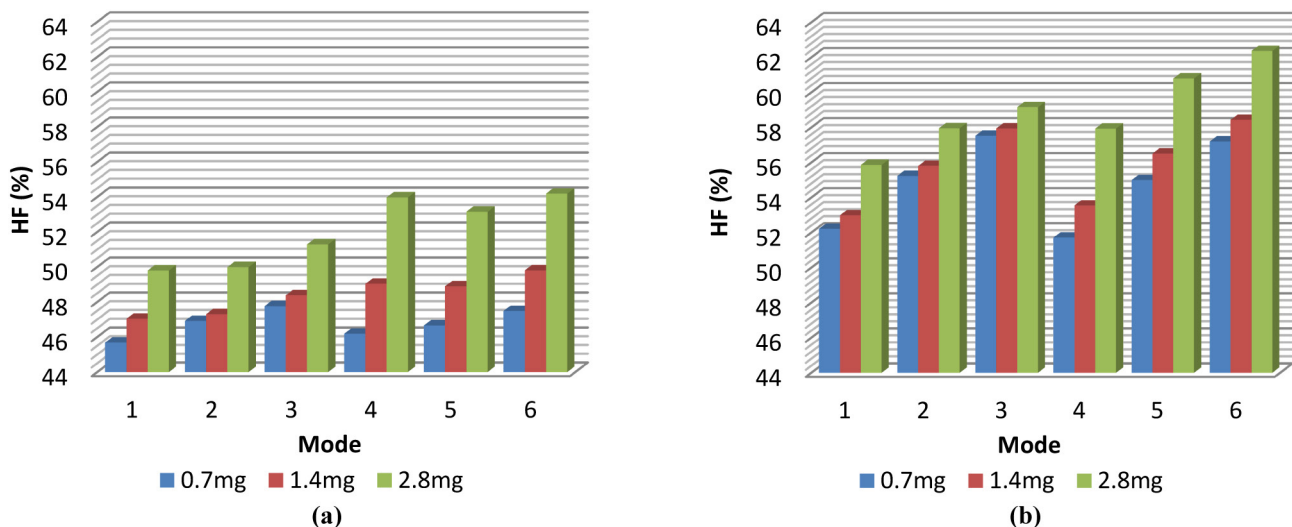


Figure 11. HF profiles for all cases at two different angles (a) angle where maximum heat release takes place (375° CA) and (b) 50% burnt location (390° CA).

All the above results can be collected and fully explained in Figure 11 which shows the in-cylinder HF at the points where maximum heat release takes place (375° CA) and at a later stage (390° CA) which is roughly the 50% burnt location.

It is clear to see that the HF is almost up to 8 units higher for the cases with 2.8mg of pilot injection compared to 0.7mg per cycle. Moreover, it is clear that the homogeneity rises as the pressure and dwell angle is increased. Cases with 15° CA dwell and 1600 bars fuel pressure have the highest in-cylinder homogeneity at 375° CA.

Engine Performance & Emissions

NOx emissions are directly influenced by the air-fuel mixing quality within the cylinder and the homogeneity percentage. Under similar testing conditions, a more complete combustion usually leads to higher in-cylinder temperatures and as a result to higher NOx formation. Figure 12 shows the NOx emissions for all the modes in terms of different pilot injection quantities. It can be clearly seen that emissions were increased dramatically as the pilot quantity was increased in all cases. This is happening due to the increase in fuel burnt in the premixed combustion at an early stage leading to a sharp temperature increase and therefore more NOx formation.

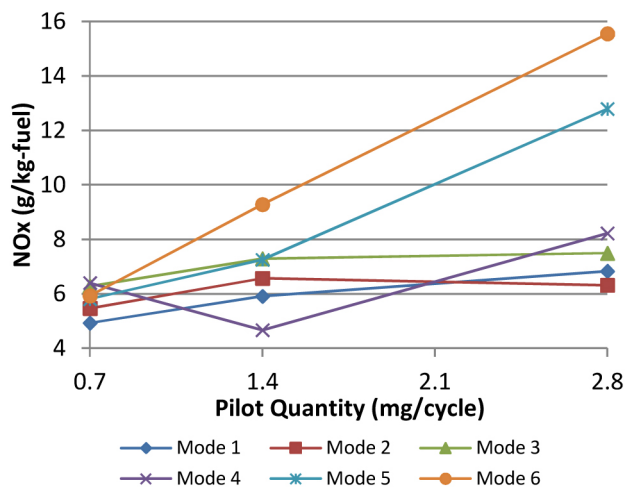


Figure 12. NOx emissions for all cases

Also, in [Figure 12](#) it can be seen that the higher dwell period (Modes 4,5 and 6) increases the NOx formation as a result of early combustion and high in-cylinder temperature rise. On the other hand, for short dwell angle cases, the pilot fuel spray works as a pre-mixing injection and the fuel is ignited only at the point where second fuel injection starts resulting to lower in-cylinder temperatures. Moreover, it can be mentioned that NOx emissions are highly influenced by the fuel injection pressure. From the [Figure 12](#) it can be seen that within the ranges tested, the higher the injection pressure is (Modes 3 and 6 at 1,600 bar compared to 2 and 5 at 1,200 bar and 1 and 4 at 800 bar), the more NOx formation. This is due to the smaller fuel droplets, leading to a faster combustion process. In addition, the NOx formation is increased for cases with larger pilot injection fuel amount. This occurs as the richer fuel combustion conditions during the pre-mixed combustion phase which is mainly responsible for the NOx generation due to the high in-cylinder temperatures experienced. However as shown in [Figure 12](#), this is not the case for Mode 4 with 1.4mg of fuel injected in the pilot pulse. This can be justified by looking back to the HRR graph of Mode 4 in [Figure 7](#) showing that this combustion case benefits from a slow HRR increment at the beginning of the pre-mixed phase compared to the 0.7mg and 2.8mg cases. Finally, it should be mentioned that comparing [Figure 12](#) with the HF figures ([Figure 7](#) and [Figure 11](#)), it is obvious for the cases tested in this research work that when the HF of a combustion analysis is increased then it leads to higher NOx formation.

[Figure 13](#) presents the soot formation over the pilot fuel quantities. It is obvious that soot formation and NOx emissions as well as soot formation and the HF follow a vice versa bend. It is clear that the cases with lower NOx and air-fuel homogeneity form higher soot than those cases with higher NOx emissions. This is happening as a result of the injection

pressure which is the main factor affecting the NOx formation and the in-cylinder homogeneity. High injection pressures lead to a mixture with less significant fuel rich regions and therefore produce less soot. At the same time, the higher combustion temperature helps to improve the soot oxidation.

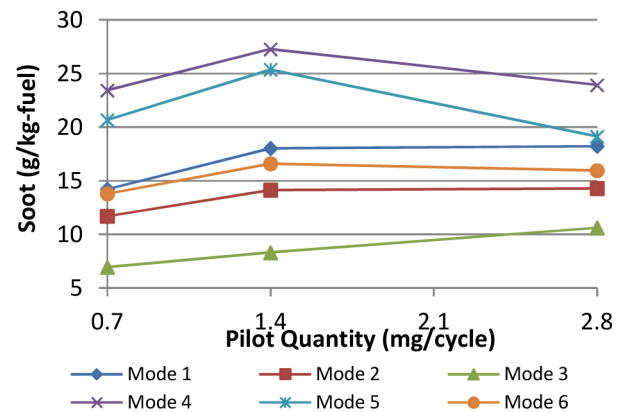


Figure 13. Soot emissions for all cases.

The pilot injection quantity increase seems to have a negative effect on the soot formation for cases with short dwell angle. This is due to the shorter reaction time for the fuel to mix with the air which leads to a less complete combustion. However, this is not happening for cases with long dwell angle due to the improved mixing process and less fuel-rich regions.

[Figure 14](#) illustrates the BSFC and IMEP trends for all the cases tested. It shows that the higher the pressure is, the higher the IMEP levels and the lower the BSFC. A more homogenous and therefore complete combustion caused by the fuel pressure increase led to better performance and lower fuel consumption. It can also be noted from [Figure 14](#) that the cases with increased pilot quantity and longer dwell angle tend to have lower BSFC and higher IMEP values. This is strongly related to the mixing process and air-fuel homogeneity. As shown in [Figure 12](#), the cases with increased pilot fuel and longer dwell angle can reach higher levels of homogeneity which results to reduced BSFC and increased IMEP values due to the fact that a more complete combustion taking place within the cylinder chamber.

Effects of Swirl Ratio on HF

Air swirl in the combustion chamber plays an important role in the mixing process between the fuel and the air but also between the partially oxidized products (soot, CO, etc.) and air. Within the ranges tested in this work, by increasing the swirl ratio, it enhances the combustion efficiency as a result of increased in-cylinder pressure and temperature caused by the optimized air-fuel mixing.

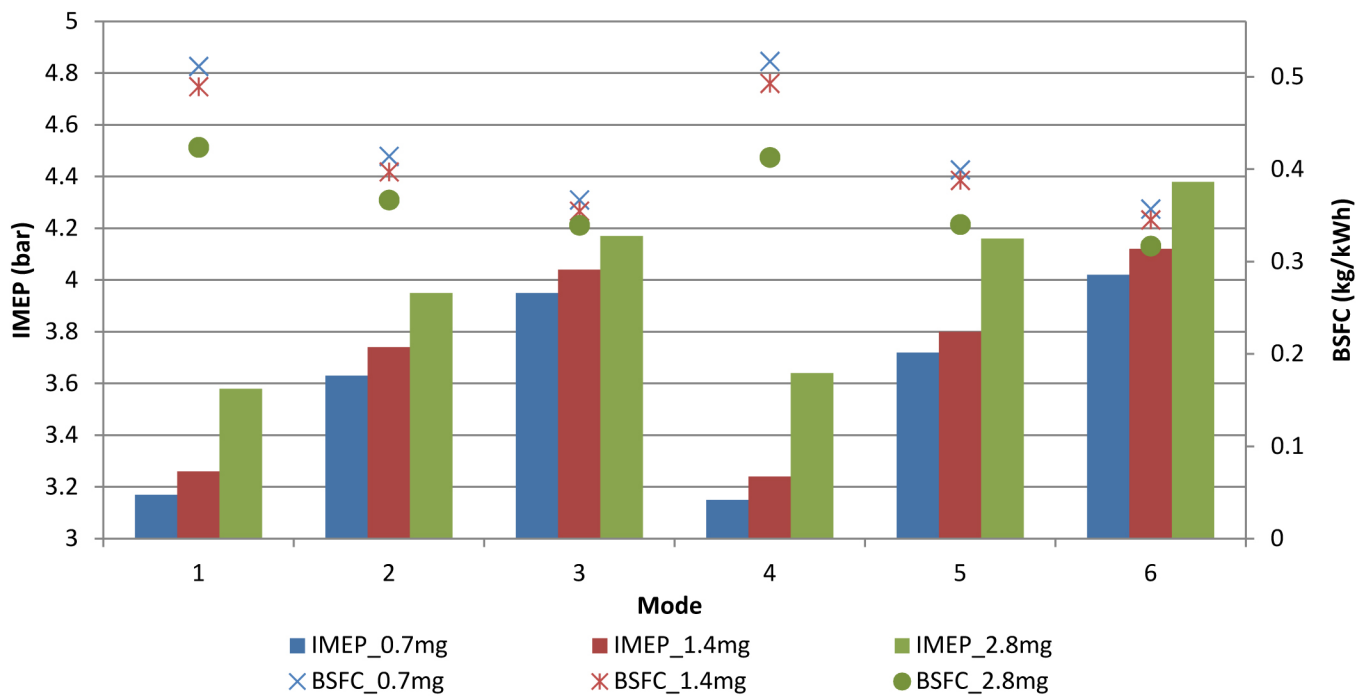


Figure 14. BSFC and IMEP results for all cases.

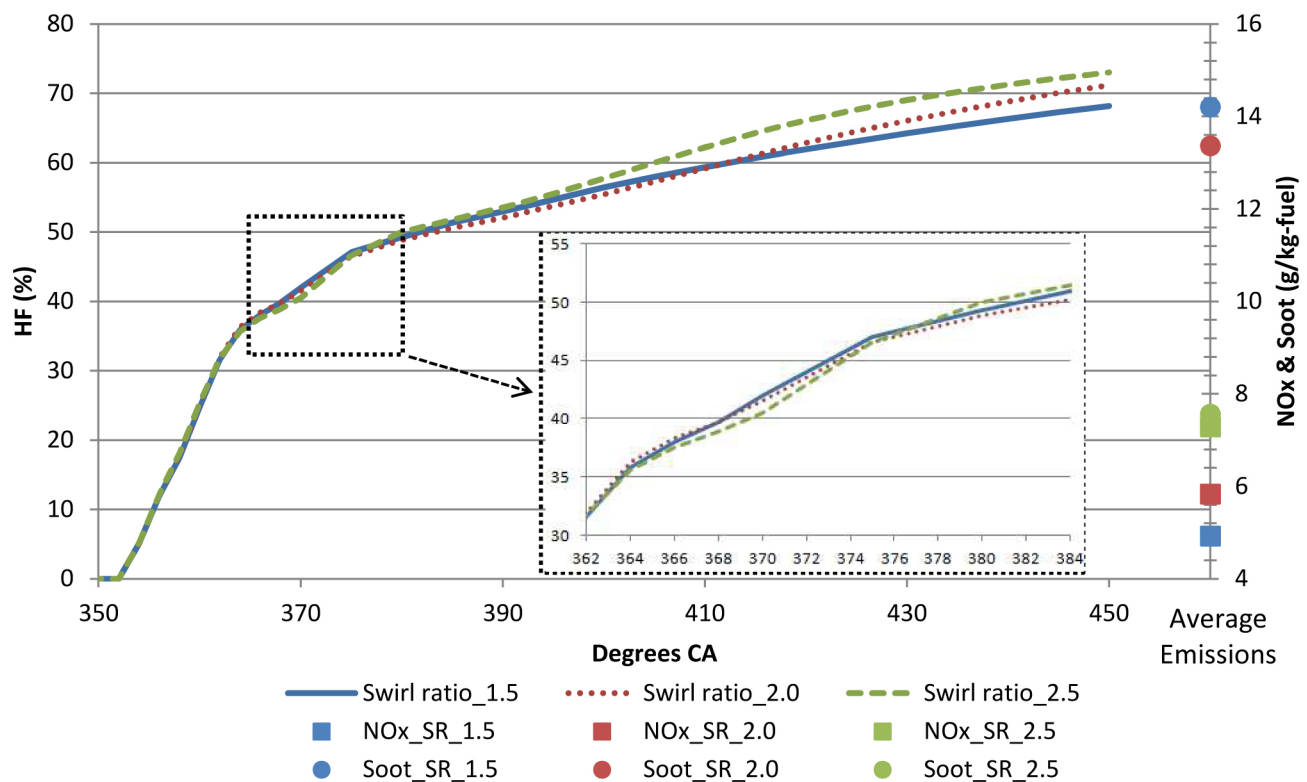


Figure 15. HF for different swirl ratio

Figure 15 illustrates the effects of air swirl effect on Mode 1 case. It proves that the mixing quality for the simulations with increased swirl motion is better than the case with swirl ratio of 1.5. As shown, the HF is slightly improved during the first pulse. Second fuel pulse seems to have a higher impact to the cases

with high swirl ratio leading to a reduced ascending ratio of the HF. This is happening due to the fact that swirling motion drags fuel droplets and vapor away from the spray centerline to the downstream volume between two adjacent sprays. This causes fuel to be distributed temporarily less homogenous within the

cylinder. After the end of second injection, the HF for the cases with high swirl ratios climbs up again which means better air-fuel mixing and thus more complete combustion. The optimized combustion can be also confirmed by the NOx emissions. It is clear that NOx are increased for cases with high swirl ratios as a result of the optimized air-fuel homogeneity. Also, this can be concluded by the high HF variance among the cases at the end of the cycle which declares that less residual fuel is left within the cylinder. On the other hand, soot formation is reduced for cases with high swirl motion. As it can be seen from Figure 15, the case with swirl ratio of 2.5 show the best combination of NOx and soot formation. The NOx emissions have been slightly increased, while the soot formation is dramatically decreased. The high soot reduction mainly occurs due to the avoidance of local fuel rich regions within the cylinder and the improved soot oxidation.

CONCLUSION

The Homogeneity Factor has been used for investigating the effects of injection pressure, pilot injection, dwell angle between injections and air swirl motion on the emissions and performance of a DI single cylinder diesel engine. The research work carried out investigates the importance of the homogeneity factor to be used as a parameter for analyzing results. It was expected that an optimized air-fuel mixing within the combustion chamber will contribute towards a reduction of fuel-dense pockets and reduce soot formation during ignition. Also, the improved air-fuel mixing was expected to contribute to lower combustion temperature and therefore less NOx formation. The main findings of this work, within the ranges tested, can be summarized as follows:

- High fuel injection pressure leads to higher in-cylinder pressure, temperature and heat release rate as a result of better fuel atomization corresponding to the smaller fuel droplets size resulting to a more complete combustion. However, high in-cylinder temperature results to an increased NOx formation.
- As the injection pressure increases, fuel is spread faster and finer into the cylinder therefore Homogeneity Factor is increased resulting to better IMEP values, less fuel consumption and soot formation.
- Increased pilot fuel quantity results to better air-fuel homogeneity and therefore higher pressure, HRR and NOx formation.
- The results show that in most of the cases an increased HF leads to improved IMEP and reduced soot formation as a result of better air-fuel mixing. However, a close connection between the HF and NOx formation cannot be established.
- The larger pilot fuel injections contribute to richer premixed combustion phase which is mainly responsible for the NOx formation due to very high in-cylinder temperatures.
- The longer the dwell angle is, the more time is available for the pilot fuel to be spread uniformly within the cylinder. This results to a more complete high in-cylinder pressure combustion and faster heat release.
- The longer the dwell angle is, the longer and slower the combustion process. Long dwell angle increases the NOx formation as a result of early in-cylinder combustion which leads to high in-cylinder temperature.
- Increasing the air swirl ratio enhances the air-fuel mixing quality which has been reflected in the variation of HF. As a result, increased in-cylinder pressure and temperature caused by the optimized air-fuel mixing improved the combustion efficiency.
- All the simulations performed in this paper clearly show that a high HF leads to a more complete combustion which has as a result in cases with similar testing conditions to increase the NOx and reduce soot emissions.

The findings of this paper partially agree with the expected results. It has been show that soot formation is highly depended on the air-fuel mixing quality, however, a strong connection between HF and NOx formation cannot be established. HF is an important parameter that can be employed for analyzing results such as air-fuel mixing quality, engine power output and soot formation. The research work carried out in this paper focuses on the effects of the injection pressure, ratio, dwell angles and swirl ratios to the air-fuel mixing quality and emissions formation and engine performance. However, there are many factors such as advancing or retarding injection timings, varying the compression ratio, EGR, turbo-charging which could all affect the HF readings, hence the engine performance and emissions. Further research is required in order to adopt HF as a combustion analysis tool that could be possibly used in the future for forecasting the emissions formation.

REFERENCES

1. Tokuda, H., "DENSO News Conference Remarks," 2003 SAE World Congress, March 4, 2003.
2. Dronniou, N., Lejeune, M., Balloul I., and Higelin, P., "Combination of High EGR Rates and Multiple Injection Strategies to Reduce Pollutant Emissions", SAE Technical Paper [2005-01-3726](#), 2005.
3. Shayler, P., Brooks, T., Pugh, G., and Gambrill, R., "The Influence of Pilot and Split-Main Injection Parameters on Diesel Emissions and Fuel Consumption," SAE Technical Paper [2005-01-0375](#), 2005, doi:[10.4271/2005-01-0375](#).
4. Eastwood, P., Morris, T., Tufail, K., Winstanley, T. et al., "The effects of fuel-injection schedules on emissions of NOx and smoke in a diesel engine during partial-premix combustion," SAE Technical Paper [2007-24-0011](#), 2007, doi:[10.4271/2007-24-0011](#).
5. Lee, J., Jeon, J., Park, J., and Bae, C., "Effect of Multiple Injection Strategies on Emission and Combustion Characteristics in a Single Cylinder Direct-Injection Optical Engine," SAE Technical Paper [2009-01-1354](#), 2009, doi:[10.4271/2009-01-1354](#).
6. Kimura, S., Aoki, O., Kitahara, Y., and Aiyoshizawa, E., "Ultra-Clean Combustion Technology Combining a Low-Temperature and Premixed Combustion Concept for Meeting Future Emission Standards," SAE Technical Paper [2001-01-0200](#), 2001, doi:[10.4271/2001-01-0200](#).

7. Pierpont, D., Montgomery, D., and Reitz, R., "Reducing Particulate and NOx Using Multiple Injections and EGR in a D.I. Diesel," SAE Technical Paper [950217](#), 1995, doi:[10.4271/950217](#).
8. Minami, T., Takeuchi, K., and Shimazaki, N., "Reduction of Diesel Engine NOx Using Pilot Injection," SAE Technical Paper [950611](#), 1995, doi:[10.4271/950611](#).
9. Mendez, S. and Thirouard, B., "Using Multiple Injection Strategies in Diesel Combustion: Potential to Improve Emissions, Noise and Fuel Economy Trade-Off in Low CR Engines," *SAE Int. J. Fuels Lubr.* 1(1):662-674, 2009, doi:[10.4271/2008-01-1329](#).
10. Montgomery, D. and Reitz, R., "Effects of Multiple Injections and Flexible Control of Boost and EGR on Emissions and Fuel Consumption of a Heavy-Duty Diesel Engine," SAE Technical Paper [2001-01-0195](#), 2001, doi:[10.4271/2001-01-0195](#).
11. Park, C., Kook, S., and Bae, C., "Effects of Multiple Injections in a HSDI Diesel Engine Equipped with Common Rail Injection System," SAE Technical Paper [2004-01-0127](#), 2004, doi:[10.4271/2004-01-0127](#).
12. Diez, A. and Zhao, H., "Investigation of Split Injection in a Single Cylinder Optical Diesel Engine," SAE Technical Paper [2010-01-0605](#), 2010, doi:[10.4271/2010-01-0605](#).
13. Tow, T., Pierpont, D., and Reitz, R., "Reducing Particulate and NOx Emissions by Using Multiple Injections in a Heavy Duty D.I. Diesel Engine," SAE Technical Paper [940897](#), 1994, doi:[10.4271/940897](#).
14. Mobasher, R., Peng, Z., Mirsalim, S. M., "Analysis the effect of advanced injection strategies on engine performance and pollutant emissions in a heavy duty DI-diesel by CFD modeling", *Int. J. Heat Fluid Flow* (2011), doi:[10.1016/j.jheatfluidflow.2011.10.004](#).
15. Eisen, S., Ofner, B. and Mayinger, F., "INVESTIGATIONS OF COMMON-RAIL FUEL INJECTION TECHNIQUE IN DI-DIESEL-ENGINES", *Proceeding of Symposium on Energy Engineering in the 21st Century*, Volume 4, 2000.
16. Badami, M., Nuccio, P., and Trucco, G., "Influence of Injection Pressure on the Performance of a DI Diesel Engine with a Common Rail Fuel Injection System," SAE Technical Paper [1999-01-0193](#), 1999, doi:[10.4271/1999-01-0193](#).
17. Agarwal, A.K., Dhar, A., Shrivastava, D.K., Maurya, R.K. and Singh, A.P., "Effect of fuel injection pressure on diesel particulate size and number distribution in a CRDI single cylinder research engine", *Fuel*, Volume 107, May 2013, pages 84-89.
18. Gumus, M., Sayin, C. and Canakci, M., "The impact of fuel injection pressure on the exhaust emissions of a direct injection diesel engine fueled with biodiesel-diesel fuel blends", *Fuel*, Volume 95, May 2012, pages 486-494.
19. DENSO Corporation, Annual Report 2011, Japan, 2011.
20. Karuppa, R.T. and Manimaran, R., "Effect of Swirl in a Constant Speed DI Diesel Engine using Computational Fluid Dynamics", *CFD Letters*, Volum 4, December 2012, p.214-224.
21. O'Rourke, P. and Amsden, A., "The Tab Method for Numerical Calculation of Spray Droplet Breakup," SAE Technical Paper [872089](#), 1987, doi:[10.4271/872089](#).
22. Tanner, F., "Liquid Jet Atomization and Droplet Breakup Modeling of Non-Evaporating Diesel Fuel Sprays," SAE Technical Paper [970050](#), 1997, doi:[10.4271/970050](#).
23. Habchi, C., Verhoeven, D., Huynh Huu, C., Lambert, L. et al., "Modeling Atomization and Break Up in High-Pressure Diesel Sprays," SAE Technical Paper [970881](#), 1997, doi:[10.4271/970881](#).
24. Patterson M. A. and Reitz R. D., "Modeling Spray Atomization with the Kelvin-Helmholtz/Rayleigh-Taylor Hybrid Model". *Atomization and Sprays*. 9. 623-650. 1999.
25. Reitz, R. D., "Modeling Atomization processes in High-Pressure Vaporizing Sprays", *Atomization and Spray Technology*, 3:309-337, 1987.
26. Kelvin, L., Thomson, W., "Hydrokinetic solution and observations", *Philosophical Magazine* 42. Pp 362-377, 1871.
27. Dukowicz, J.K., "Quasi-steady droplet phase-change in the presence of convection", Technical Report LA-7997-MS, Los Alamos Scientific Laboratory, 1979.
28. Hanjalic, K., Popovac, M., Hadziabdic, M., "A robust near-wall elliptic-relaxation Eddy-viscosity turbulence model for CFD", *Int. J. Heat and Fluid Flow* (2004), 25, 6:1047-1051.
29. Jones, W.P., Launder, B.E., The prediction of laminarization with a two-equation model of turbulence, *Int. J. Heat Mass Transfer*, 15, p. 301, 1972.
30. Yakhot, V., Smith, L.M., The renormalization group, the ϵ -expansion and derivation of turbulence models, *J. Sci. Comp.*, 7:35-61, 1992.
31. Colin, O., Benkenida, A., "The 3-zones extended coherent flame model (ECFM3Z) for computing premixed/diffusion combustion", *Oil & Gas Science and Technology*, 2004, Rev. IFP. 159, 6, str. 593-609.
32. Heywood, J. B., "Internal Combustion engine Fundamentals", McGraw-Hill. Inc., ISBN 0-07-028637-X, 1988.
33. ICE Physics & Chemistry, AVL FIRE User Manual v.2009. 1, 2009.
34. Peng, Z., Liu, B., Tian, L., and Lu, L., "Analysis of Homogeneity Factor for Diesel PCCI Combustion Control," SAE Technical Paper [2011-01-1832](#), 2011, doi:[10.4271/2011-01-1832](#).
35. Nandha, K. and Abraham, J., "Dependence of Fuel-Air Mixing Characteristics on Injection Timing in an Early-Injection Diesel Engine," SAE Technical Paper [2002-01-0944](#), 2002, doi:[10.4271/2002-01-0944](#).
36. Siebers, D., "Liquid-Phase Fuel Penetration in Diesel Sprays," SAE Technical Paper [980809](#), 1998, doi:[10.4271/980809](#).
37. Siebers, D., "Scaling Liquid-Phase Fuel Penetration in Diesel Sprays Based on Mixing-Limited Vaporization," SAE Technical Paper [1999-01-0528](#), 1999, doi:[10.4271/1999-01-0528](#).

ACKNOWLEDGMENTS

This work was produced in the framework of SCODECE (Smart Control and Diagnosis for Economic and Clean Engine), a European territorial cooperation part-funded by the European Regional Development Fund (ERDF) through the INTERREG IV A 2 Seas Programme.

The authors acknowledge the AVL Company to provide computational resources for this research.

DEFINITIONS/ABBREVIATIONS

ATDC - After Top Dead Centre

BDC - Bottom Dead Centre

BSFC - Brake Specific Fuel Consumption

BTDC - Before Top Dead Centre

CA - Crank Angle

CFD - Computational Fluid Dynamics

CFM - Coherent Flame Model

DOH - Degree of Heterogeneity

ECFM-3Z - Extended Coherent Flame Model - 3 Zones

EGR - Exhaust Gas Recirculation

EVO - Exhaust Valve Opening

HF - Homogeneity Factor

HeterF - Heterogeneity Factor

HRR - Heat Release Rate

HSDI - High-Speed Direct Injection

IMEP - Indicated Mean Effective Pressure

IVC - Inlet Valve Closure

NOx - Oxides of Nitrogen

PCCI - Premixed Charge Compression Ignition

ppm - parts per million

SOI - Start of Injection

TDC - Top Dead Centre

uHC - unburned Hydrocarbons

VGT - Variable Geometry Turbocharger